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Narrow-Body Aircraft Water Spray Optimization Study

Timothy R. Marker

February 1993

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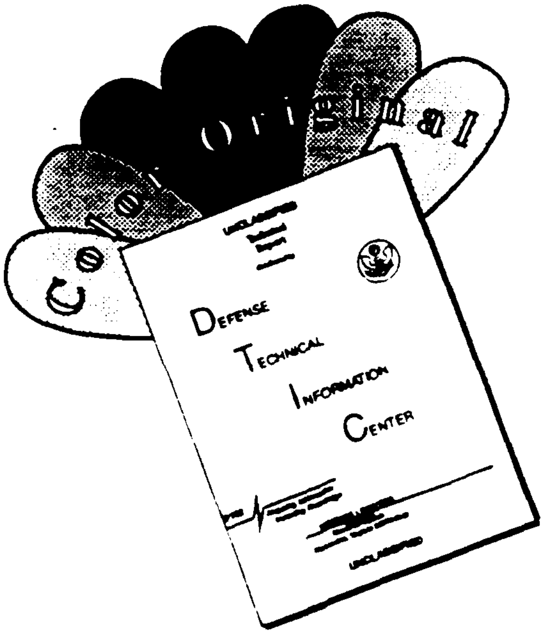

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16. Abstract

Twenty-five full-scale tests were conducted in a modified 707 narrow-body fuselage as part of an aircraft cabin water spray optimization study. The purpose of the study was to test several spray configurations by varying the amount of water sprayed, the flow rate, and orientation of the nozzles, while keeping the fire conditions constant, in an attempt to minimize the quantity of water required to effectively suppress a postcrash aircraft fire and improve occupant survivability.

The original Safety Aircraft and Vehicles Equipment (SAVE) system was configured in the narrow-body cabin using 120 nozzles. Initially, three tests were conducted using 72, 48, and 24 gallons of water for 3-, 2-, and 1-minute spray durations, respectively. In the following series of tests, one-third of the SAVE system (40 nozzles) was configured in the area of the fire using 24, 16, and 8 gallons of water for 3-, 2-, and 1-minute spray durations, respectively. During the final series of tests, the spray system was configured in five separate sections or "zones" with each zone carrying eight nozzles. A thermocouple was mounted at ceiling height in each zone, allowing for the activation of a particular zone when the temperature reached a predetermined value. The flow rate of the nozzles was varied as was the amount of water available during the tests. For comparison, a test was conducted without spraying water in order to establish a "baseline." Temperature, heat flux, smoke levels, gas concentrations, and video were continuously monitored at various locations throughout the fuselage. The optimal zoned system was more efective than the SAVE system and used only 11 percent of the water.

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EXECUTIVE SUMMARY

A safety improvement beyond the fire hardening of cabin interior materials is a low flow rate onboard cabin water spray system (CWSS). Originally developed by SAVE (Safety Aircraft and Vehicles Equipment) Ltd., the system consists of an array of nozzles located throughout the cabin, filling the entire volume with a fine mist. Although the system can offer an additional 2 minutes of escape time in typical postcrash fire scenarios, the present design adds a significant amount of weight. In an effort to curtail the weight penalty, a study was undertaken to test and develop a system which could provide a level of protection equivalent to, or better than, the level of protection offered by the SAVE CWSS by using less water and, hence, less weight.

Twenty-five tests were conducted in a modified 707 fuselage to investigate the performance of an optimized CWSS by varying the flow rate, discharge duration, and orientation of the nozzles. Previous tests had shown that the best method of maximizing the effectiveness of water is to localize the spray, discharging it only in the immediate vicinity of the fire threat. By eliminating the amount of wasted spray in remote areas of the cabin, more efficient use of the water spray is facilitated. The benefits are twofold, however, since this method also allows the layer of smoke and gases to "restratify" in the more remote areas of the cabin, the likely location of passengers attempting to deplane in the event of an emergency.

The optimized spray system was divided into five zones which could be individually activated when the temperature reached a predetermined value of 300 °F, as measured by a ceiling mounted thermocouple in the center of each zone. The system showed that a small quantity of water was very effective in safeguarding against the effects of an external fuel fire. As much as 159 seconds of additional time available for escape can be achieved by using only 8 gallons of water.

INTRODUCTION

PURPOSE.

The purpose of this report is to present the results of 25 full-scale fire tests which utilized a cabin water spray system for the suppression of a postcrash aircraft fuel fire. The tests investigated the ability of an optimized spray system, comprised of a series of spray zones with independent discharge activation based on zone temperature, at providing a level of protection equivalent to or better than a full cabin spray system.

BACKGROUND.

The onboard cabin water spray program is comprised of several phases aimed at developing a safe and effective system for installation in a commercial transport aircraft (reference 1). Initial full-scale effectiveness tests were performed using the Safety in Aircraft and Vehicles Equipment (SAVE), Limited, cabin water spray system. Although the SAVE system was found to offer an additional 2 minutes of escape time in both the narrow-body and wide-body fuselages under some fire scenarios, it was designed to spray water throughout the entire cabin and overhead area for 3 minutes. This required 72 gallons of water in a typical narrow-body configuration and 195 gallons in the wide-body, which constituted a substantial weight penalty. Subsequent tests showed that the removal of the water spray from the cabin overhead area resulted in insignificant reduction in the additional escape time offered by the system (reference 2). Other tests showed the effectiveness of spraying water only in a section of the cabin area nearest to the immediate fire threat, thereby reducing the amount required (reference 3). Concurrent to these initial tests, a study was undertaken to address the various service considerations or "disbenefits" associated with an onboard water spray system. The results of these initial studies are presently being factored into a benefit analysis to determine the potential for lives saved. If the benefits of such a system outweigh the disbenefits, the next phase will be to optimize the system and, later, to develop design requirements and specifications. In anticipation of a favorable benefit analysis, the optimization phase was undertaken in an effort to develop a system which would provide a level of protection equivalent to or better than the full spray system using a fraction of the water. The approach taken, as suggested by earlier test results, was to zone the aircraft and spray water only where there was a fire or high temperatures, or "localizing" the spray, thereby enabling more effective use of the water.

DISCUSSION

TEST DESCRIPTION.

Twenty-five tests were conducted in a fully fire hardened B707 fuselage, representing a typical narrow-body, single aisle aircraft cabin. Of the 25 tests conducted, 20 utilized a full fire load of seats, panels, and carpet while 5 of the tests were run using an empty fuselage (7 of the 25 tests are omitted from this report due to lack of toxic gas data). As shown in figure

1, the interior fire load during the full material tests consisted of three rows of fire blocked seats, four sidewall panels, four stowage bins, and carpet. All tests utilized a standard 8- by 10-foot pan fire adjacent to a type A door opening, with 55 gallons of JP-4 fuel used to create the pan fire. The fire was drawn into the fuselage by an exhaust fan mounted in the ceiling of the forward cabin section, simulating a wind-induced cabin draft.

After two initial "shakedown" tests in which the instrumentation was inspected, a test was run without introducing water spray into the cabin in order to establish "baseline" data. Following this, three tests were conducted using the full SAVE system for 3-, 2-, and 1-minute spray durations which required 72, 48, and 24 gallons of water, respectively (figure 2). (Past accident data have shown that during a crash and subsequent fuselage breakup, the separation usually occurs forward and aft of the wings. For this reason, it is conceived that an onboard system would consist of three water supply tanks so that there would be a minimum of one-third of the total water supply available in the event of a breakup). During the second series of tests, one-third of the full SAVE system was configured in the area of the type A opening. This required a total of 40 nozzles, covering approximately 30 feet in cabin length (figure 3). The testing consisted of 3-, 2-, and 1-minute spray durations requiring 24, 16, and 8 gallons of water, respectively. The nozzles used for the first six tests were Unijet "D" type with a 90° hollow cone spray pattern and, for all practical purposes, were equivalent to the SAVE system nozzles. The nozzles utilized a 0.078-inch disc orifice diameter (D5) and a #23 core arrangement to yield an average flow rate of 0.23 gallons per minute (GPM).

During the final series of tests, the nozzles were configured in a "zoned" arrangement consisting of five zones, with eight nozzles in each zone (figure 4). The zones are 8 feet in cabin length and include four spray nozzles mounted at the cabin periphery in each of the two boundary planes, with the spray discharge directed towards the center of the zone. Specifically, each nozzle is mounted perpendicular to the supply line and at a 45° angle with the vertical traverse plane (figure 5). After several preliminary tests, a temperature of 300 °F was selected to activate the water discharge manually. The temperature in each zone is measured by a thermocouple which is centrally located at the ceiling level. The average flow rate for the initial zoned tests was 0.23 GPM per nozzle using a disc and core arrangement identical to that used in the SAVE tests. The nozzle pressure used during the zoned tests (80 pounds per square inch (psi) at the supply tank) was slightly higher than the pressure used during the SAVE tests since only one supply line from the tank was used to feed all five of the zones. Tests were conducted using 24, 16, and 8 gallons of water at this flow rate. The disc and core arrangement was then changed to yield a 0.35 GPM flow rate by using a 0.063-inch disc orifice diameter (D4) and #25 core. Two tests were conducted at this flow rate using 24 and 8 gallons of water. Lastly, three tests were conducted using 24, 16, and 8 gallons of water at an increased flow rate of 0.50 GPM per nozzle. This was accomplished by using a 0.094-inch disc orifice diameter (D6) with the #25 core. The tank pressure was at 80 psi for all the zoned tests.

The fuselage was outfitted with thermocouple trees, smoke meters, calorimeters, gas sampling stations and video cameras which monitored the conditions inside the cabin. A description of the instrumentation follows.

THERMOCOUPLE TREES. Six thermocouple trees continuously measured the temperature throughout the cabin. The trees were located at 400, 590, 780, 970, 1160 (type A opening location), and 1380 inches from the nose of the aircraft. Each tree consisted of seven thermocouple probes positioned from 1 foot above the floor to 7 feet above the floor. The 7-foot location was approximately ceiling level.

SMOKE METERS. Smoke meter (light transmission) stations were located at 400 and 780 inches from the nose. Each station contained three smoke meters positioned at 18, 42, and 66 inches from the floor level. The smoke meters consisted of a collimated light source and photocell separated by 1 foot.

GAS ANALYSIS. Continuous gas sampling stations used to measure carbon monoxide, carbon dioxide, and oxygen were located at 400 and 780 inches from the nose. Each station had intakes at heights of 42 and 66 inches from the floor.

CALORIMETERS. Calorimeters were used to measure the heat flux at four locations: 590, 780, 1160, and 1380 inches. The transducers were all mounted at a height of 42 inches along the fuselage centerline. At stations 590 and 780 the transducers were facing aft; at station 1380, the transducer was facing forward. The transducer located at station 1160 was facing directly toward the fire door.

TEST RESULTS

Due to the enormous amount of data compiled during the 25 tests, the analysis is limited to the zoned tests and certain data. The analysis compares the results of these tests based on temperature profiles, gas concentrations, and smoke levels within the cabin. In order to determine the effect the various hazards have on survivability, a fractional effective dose (FED) model was used to calculate the survival time at a forward location in the cabin. The recently developed model utilizes the best available data to determinine the incapacitation of humans subjected to heat and toxic combustion gases. It assumes that the effect of heat and each toxic gas on incapacitation is additive. The model also assumes that the increased respiratory rate due to elevated levels of carbon dioxide is manifested by enhanced uptake of other gases. In addition, the increase in survival time offered by using the zoned water spray arrangement is compared on the basis of nozzle flow rate and quantity of water used to determine which combination offers the greatest improvement in survivability per gallon of water sprayed.

TEMPERATURE PROFILES.

Figure 6 shows the temperature range between 3 and 5 feet above floor level at station 400. As indicated, there is a significant reduction in cabin air temperature during water spray tests in comparison to the baseline test. More important, however, is the fact that by spraying as little as 8 gallons of water, the cabin temperatures are reduced to nearly the level attained during the full 3-minute SAVE test in which 72 gallons of water were sprayed.

Figures 7, 8, and 9 compare the temperature profiles at 4 feet above floor level at station 400 for the various "zoned" spray tests. Realistically, the temperature profiles for these tests should fall between the baseline test and the full 3-minute SAVE test in which water was sprayed throughout the cabin; both the baseline and SAVE tests are displayed in each of these figures for comparison. Figure 7 compares the results of the 24-, 16-, and 8-gallon zoned tests using a nozzle identical to that used in the full SAVE test, which provided a flow rate of 0.23 GPM. As expected, the temperatures were highest during the 8-gallon zoned test, slightly lower during the 16-gallon test, and lowest when 24 gallons of water were sprayed. Figure 8 shows the temperature profiles of three additional zoned tests which utilized a slightly higher flow rate nozzle (0.35 GPM). The 24- and 8-gallon zoned tests yielded temperatures even lower than those obtained during the previous tests in which the flow rate was 0.23 GPM. Because the higher flow rate nozzles yielded a greater temperature reduction, they were changed to an even higher flow rate of 0.50 GPM. Tests were performed using quantities of 24, 16, and 8 gallons of water (figure 9). Although the 24-gallon test offered the greatest reduction in temperature at this flow rate, the 8-gallon test surprisingly yielded a lower temperature profile than the 16-gallon test. (The only reasonable explanation that can be offered is that an exceptionally long period of time transpired prior to fuel ignition, after the pan was filled with JP-4 before the 16-gallon tests, due to an unrelated malfunction. With the exhaust fan operating inside the cabin during this period, a significant amount of fuel vapor may have been drawn into the cabin, possibly creating a more volatile atmosphere prior to test commencement).

A comparison of the three different flow rate tests shows that the 0.35 GPM nozzles offered the greatest temperature reduction for a specific quantity of water. Another determining factor is the duration of the water spray. During the 24-gallon tests, for example, the spray lasted 230 seconds for the lower flow rate (0.23 GPM), 180 seconds for the medium flow rate (0.35 GPM), and 140 seconds for the higher flow rate (0.50 GPM).

GAS ANALYSIS.

Figures 10 through 15 represent the toxic gas levels of carbon monoxide (CO), carbon dioxide (CO_2), and oxygen (O_2) at a forward location within the cabin. Figure 10 shows the CO concentration between 3 feet 6 inches and 5 feet 6 inches above floor level for the baseline test, 3-minute SAVE test, and the 8-gallon zoned test (0.35 GPM flow rate). Clearly, the greatest level of CO production occurs during the baseline test, reaching a 2 percent concentration at approximately 150 seconds (2 percent is the maximum concentration measured by the gas analyzers). During the full 3-minute SAVE test, the level was reached in approximately 300 seconds. More interesting, however, is that the level of CO production was actually lower during the 8-gallon zoned test than during the full SAVE test in which 72 gallons of water were sprayed. Figure 11 confirms this finding; at a height of 3 feet 6 inches, all of the zoned tests produced CO levels lower than both the baseline test and the 3-minute SAVE test. The most logical explanation for this occurrence is that the zoned tests allow for the combustion gases to "restratify" in the forward cabin locations. In comparison, by spraying water at ceiling height in these forward locations (as in the full SAVE system test), the layer of gases is pulled downward nearer to the gas sampling heights. As was the case with the

temperature profiles, the 0.35 GPM flow rate nozzle produced the most favorable cabin environment during both the 24- and 8-gallon tests.

In figure 12, the CO_2 level between 3 feet 6 inches and 5 feet 6 inches is shown for the baseline test, the 3-minute SAVE test, and the 8-gallon zoned test. The results duplicate the comparisons of the CO production (figure 10), again showing that during the 8-gallon zoned test, there was a lower level of gas concentration than during the 3-minute, 72-gallon SAVE test. Similarly, figure 13 displays the CO_2 production for the other zoned tests at this location at a height of 3 feet 6 inches (for clarification purposes, the CO_2 levels are displayed at a single height rather than over a range). Not surprisingly, the lowest concentrations of CO_2 occurred during the 24- and 8-gallon zoned tests that utilized the 0.35 GPM flow rate nozzles. The depletion of oxygen within the cabin parallels the production of CO and CO_2 for all tests in a nearly identical manner (figures 14, 15).

SMOKE LEVELS.

Figure 16 shows a comparison of the smoke levels at station 780 between the heights of 1 foot 6 inches and 3 feet 6 inches for three tests: baseline, 3-minute SAVE, and 8-gallon zoned. As shown, there is a substantial decrease in visibility during the 3-minute SAVE test, well in advance of the time that this occurred during the other two tests. This occurrence is similar to that of the CO and CO_2 production discussed in the previous section on gas analysis. The mechanism that causes the increased smoke (decreased visibility) earlier during the SAVE test is the result of spraying water throughout the entire cabin; this drives down the otherwise stratified layer of smoke and gases to lower cabin levels. Conversely, the visibility remains more favorable during the 8-gallon zoned test since the smoke and gases are permitted to "restratify" to higher cabin elevations in the nonsprayed areas. This behavior can also be seen at a more forward cabin location, between a height of 3 feet 6 inches and 5 feet 6 inches (figure 17). Figure 18 compares the smoke levels of the 24- and 8-gallon tests using both the 0.23 and 0.35 GPM flow rate nozzles (for clarification purposes, the curves have been "smoothed" to eliminate most of the overlap between the tests, which is confusing). As shown, the best overall visibility is sustained during the 8-gallon test at the 0.35 GPM flow rate, followed by the 8-gallon test using the 0.23 GPM flow rate. The 24-gallon test using the 0.35 GPM flow rate yields slightly better visibility than the 0.23 GPM flow rate. At this location there appears to be a correlation between the duration of water spray and the degree of visibility; the percentage of light transmission remained highest during the 8-gallon test at the higher of the two flow rate nozzles compared, which was of the shortest duration (approximately 90 seconds).

FRACTIONAL EFFECTIVE DOSE.

Figures 19 through 22 show the survival times in the forward cabin as calculated by the fractional effective dose (FED) model. All figures show the baseline FED calculation for comparison. In figure 19, the 3-minute full SAVE system test is compared to the "sectional" SAVE test in which one-third of the SAVE system was installed in the area of the fire door. As shown, there is actually an increase in the survivability by using only one-third the amount of water used in the full SAVE test. By allowing the layer of smoke and gases

to restratify in the forward section of the cabin, there is essentially a lower concentration of the toxicants at the sampling height (5 feet 6 inches), thereby yielding the more favorable FED calculation.

In figure 20, the zoned tests of 24, 16, and 8 gallons using the 0.23 GPM flow rate nozzle were compared. During the baseline test, conditions became nonsurvivable (FED=1) at this location in 128 seconds. The 24-gallon zoned test increased the survival time to 210 seconds, an addition of 82 seconds. During the 16-gallon zoned test the survival time was increased to 219 seconds, an increase of 91 seconds. Most interesting was the additional 132 seconds of survival time gained when only 8 gallons of water were sprayed. The reason for the unusually high survival times recognized during the lower quantity spray tests was due to the dominance of the CO in the FED calculation. During the tests in which the greater quantity of water was sprayed, there seemed to be slightly less restratification; this in turn caused higher levels of gases at the sampling height, particularly CO. This occurrence was possibly the result of the greater spray duration encountered during these tests, which led to more mixing within the cabin and subsequently reduced the ability of the smoke and gases to restratify.

The measurement location of the hazards also dictates which hazard will have a more dominant effect in the FED model (i.e., if the measurement location is closer to the fire, the temperature will be the driving factor; at a more remote location, the gases will be the principal factor).

Figure 21 shows the FED comparisons for the zoned tests using a nozzle flow rate of 0.50 GPM. The calculated survival times for the 24- and 8-gallon tests were nearly identical: 269 and 262 seconds, respectively. The FED curves indicate identical conditions up to 90 seconds, then slightly worse conditions for the 24-gallon test between 90 and 200 seconds. After 200 seconds, the conditions during the 8-gallon test became the less favorable of the two. This further demonstrates the effects of increased mixing, since the discharge period for the 24-gallon test was approximately 150 seconds, compared to only 90 seconds for the 8-gallon test. As a result of the increased mixing, higher levels of CO and CO_2 are encountered, as well as more O_2 depletion. In contrast to the 24- and 8-gallon tests, the 16-gallon test yielded a survival time substantially lower, only 220 seconds. A reasonable explanation for this was due to the previously described lengthy delay between the time the fuel was poured into the fire pan and the point of ignition.

Figure 22 shows the FED curves for the tests utilizing the 0.35 GPM flow rate nozzles. The cabin environment at this location again became nonsurvivable at a nearly identical time for both the 8- and 24-gallon zoned tests. The conditions were more favorable for a majority of the time during the 8-gallon test, again the result of slightly lower levels of CO and CO_2, and less O_2 depletion at this locale. In general, the zoned tests using the lesser quantities of water yielded more favorable cabin conditions for the 0.23 and 0.35 GPM flow rates.

In order to determine at what point an even lesser quantity of water spray would cease to yield more favorable conditions, a test was run using only 4 gallons of water at the 0.35 GPM flow rate. As shown in figure 22, this

amount of water did not produce cabin conditions more favorable than the 8-gallon test at this flow rate. The optimum spray quantity for this flow rate is therefore between 4 and 8 gallons.

In an effort to quantify the effectiveness of the water spray during the various zoned tests, a graph was generated that plotted the additional seconds of escape time per gallon of water spray used ("seconds per gallon" or SPG) versus the nozzle flow rate (figure 23). This determined which flow rate nozzle produced the most favorable cabin conditions using the least amount of spray. Figure 24 displays the calculations that were performed to develop the data points for each test. Of the nine zoned tests conducted, the 0.35 GPM flow rate nozzle yielded the most survivability per gallon of water used (during the 8-gallon test). The least efficient use of water spray occurred during the 24-gallon test using the 0.23 GPM flow rate. These results are based upon survivability considerations at a particular cabin location and height (station 400, 5 feet 6 inches).

SUMMARY OF RESULTS

In general, there exists a direct correlation between the amount of water sprayed and the cabin air temperature; for a given nozzle flow rate, the greater the quantity of water sprayed, the lower the temperature. Temperatures were lowest during the 72-gallon full SAVE test, and with exception of one test, increased steadily as the quantity of water sprayed decreased; temperatures were the highest when no water was sprayed (baseline). The primary mechanism responsible for the direct correlation between cabin air temperature and quantity of water sprayed is simply the ability of the water spray to reduce the burning rate of the materials for a greater length of time during the higher quantity spray tests.

This type of correlation did not exist between water quantity and level of toxic gases, as the concentration was actually higher during the zoned tests in which a greater quantity of water was sprayed. During the tests utilizing greater spray quantities, there was a longer period of time that the combustion gases were being transported away from the fire area and into the more remote areas of the cabin due to the mixing action of the spray nozzles. This increased turbulence diminished the ability of the gases to restratify into a uniform layer at ceiling height, and subsequently caused higher concentrations of these gases at the sampling station height of 5 feet 6 inches.

The restratification effect was substantiated by examining the level of smoke during the various zoned tests, which is usually analogous to the gas concentration. The results also indicated slightly higher levels of smoke (at the lower measuring heights) during the tests in which a greater amount of water was sprayed. This trend is quite possibly a function of the water spray duration, as the shorter discharge time tests (lesser water quantity) had yielded the most favorable amounts of visibility.

CONCLUSION

As shown by the test results, the best technique for maximizing the usefulness of the water spray is to divide the system into segments or "zones" that allow for better control of the water spray, thereby minimizing the amount of waste. This technique also has the added benefit of yielding increased visibility in comparison to a system which sprays throughout the entire cabin. The visibility increase is the result of restratification of the smoke and gas layer in the areas of the cabin that are more remote to the direct fire threat.

After determining the additional survival time obtained during the various zoned tests, a "seconds per gallon" calculation gave an estimate of the most efficient nozzle arrangement in terms of added benefit for the least possible weight penalty. For this particular system configuration in which the five zones were 8 feet in cabin length, a nozzle flow rate of 0.35 GPM yielded the best level of protection for the least amount of water sprayed (a mere 8 gallons). This nozzle flow rate also yielded the largest overall increase in survivability when 24 gallons of water were used. An additional 161 seconds of survival time were obtained by utilizing this nozzle configuration and quantity of water (at the calculated cabin location.)

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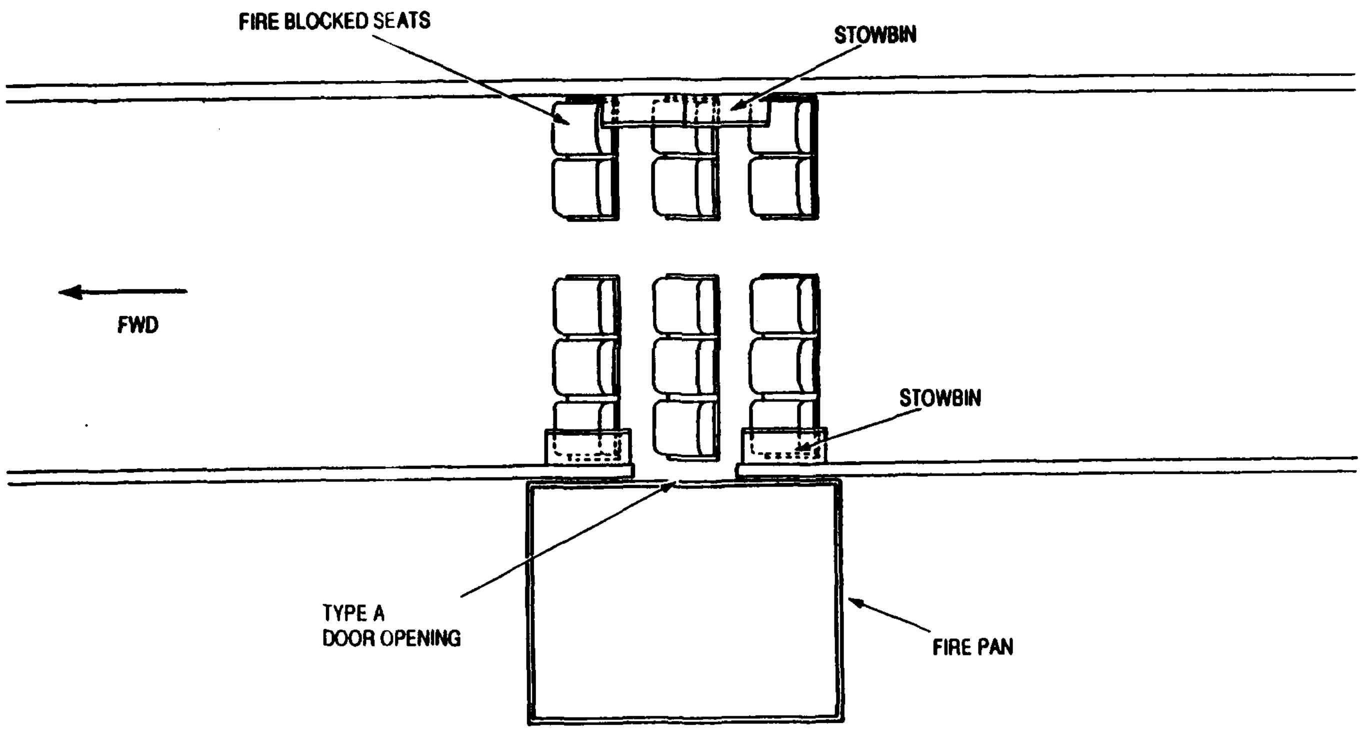


FIGURE 1. CABIN CONFIGURATION

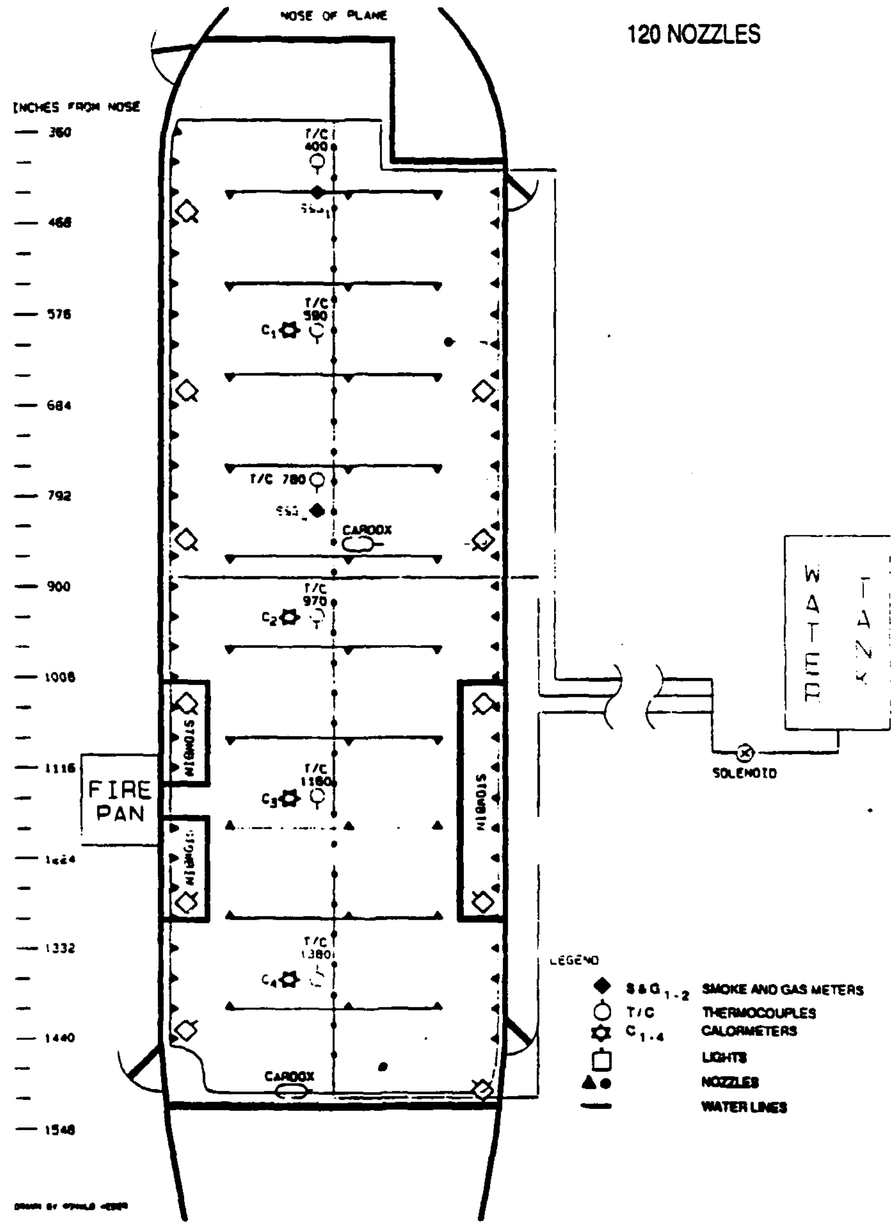


FIGURE 2. SAVE WATER SPRAY SYSTEM

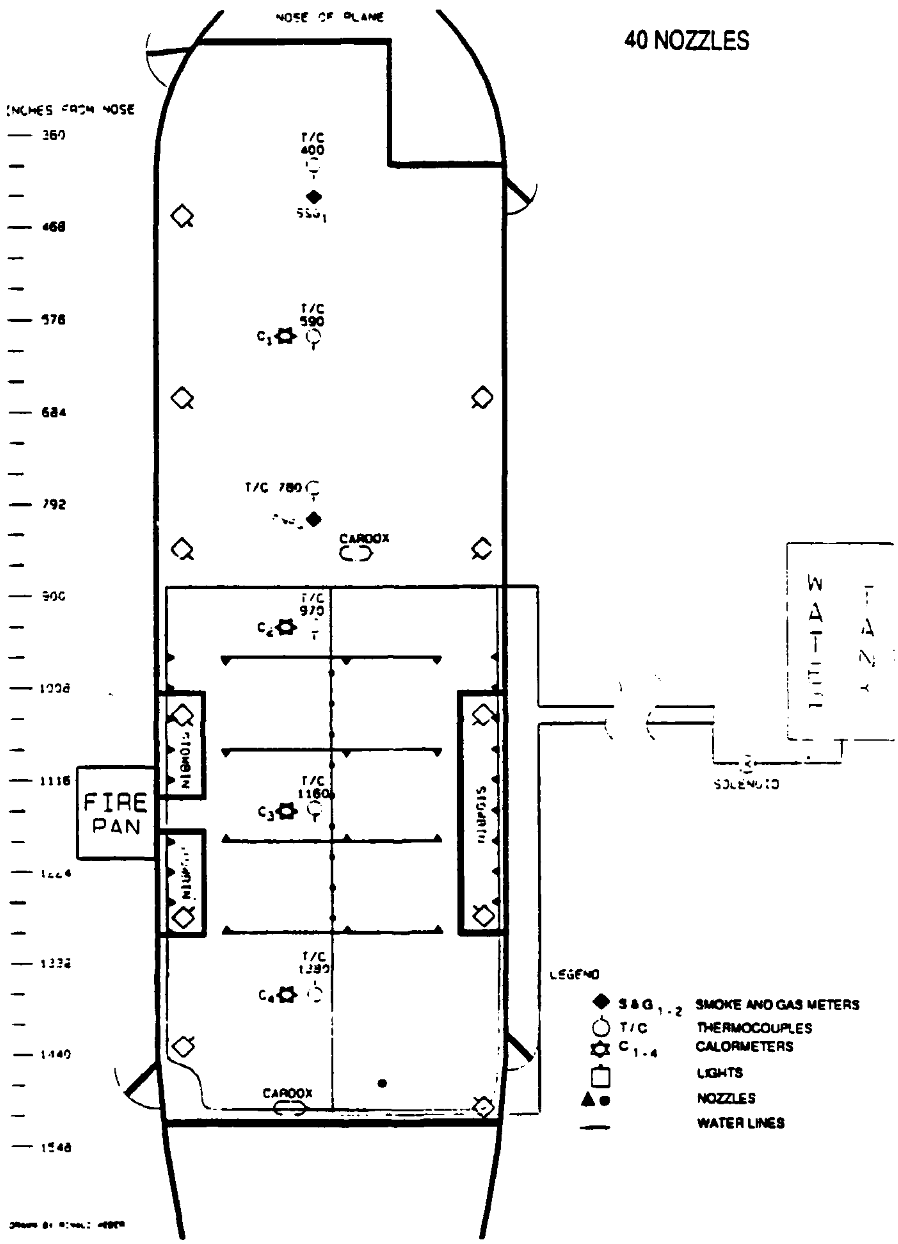


FIGURE 3. SECTIONAL SAVE WATER SPRAY STSTEM

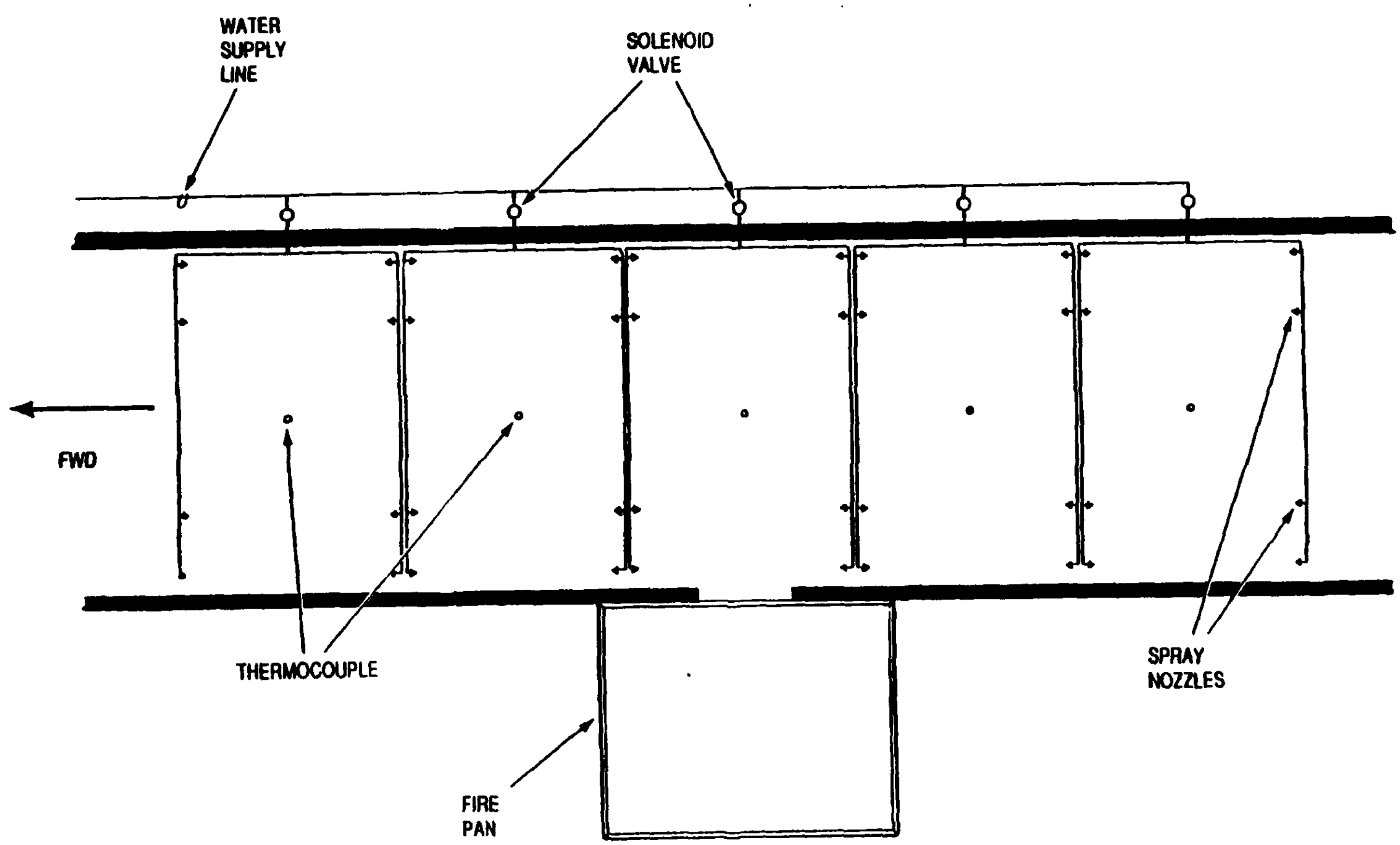


FIGURE 4. ZONED SPRAY CONFIGURATION

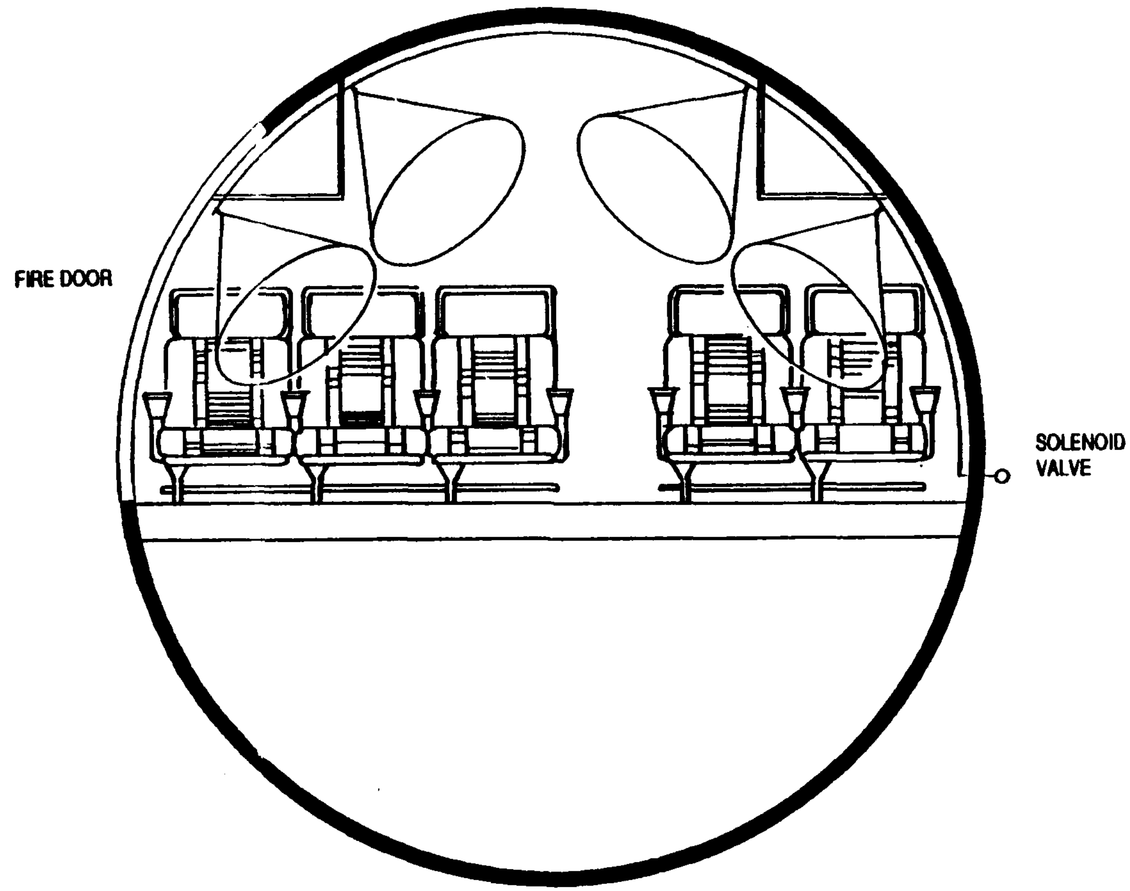


FIGURE 5. ZONED WATER SPRAY SYSTEM NOZZLE ARRANGEMENT

FIGURE 6. TEMP @ STA 400 3' TO 5'

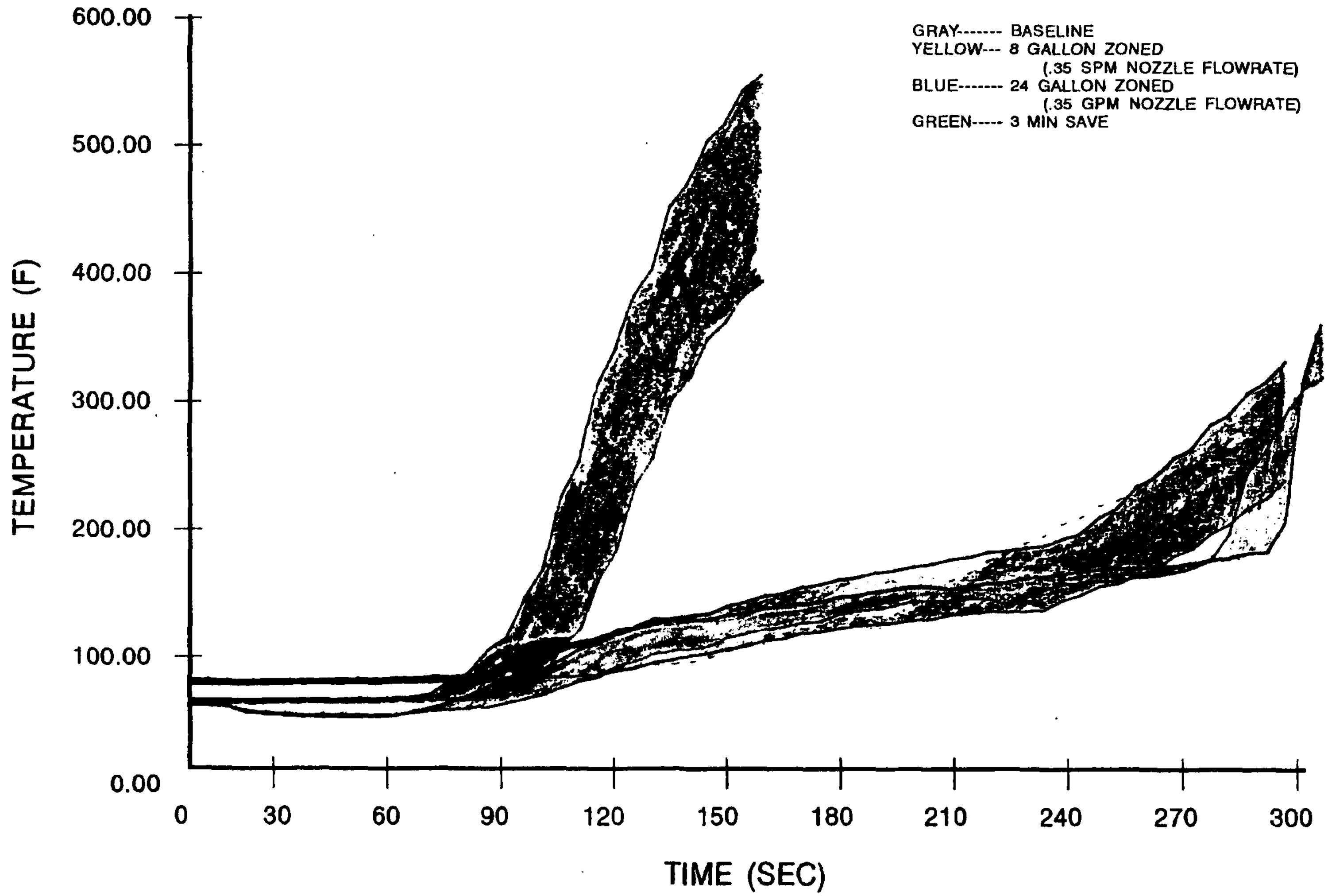


FIGURE 7. TEMP @ STA 400 4'

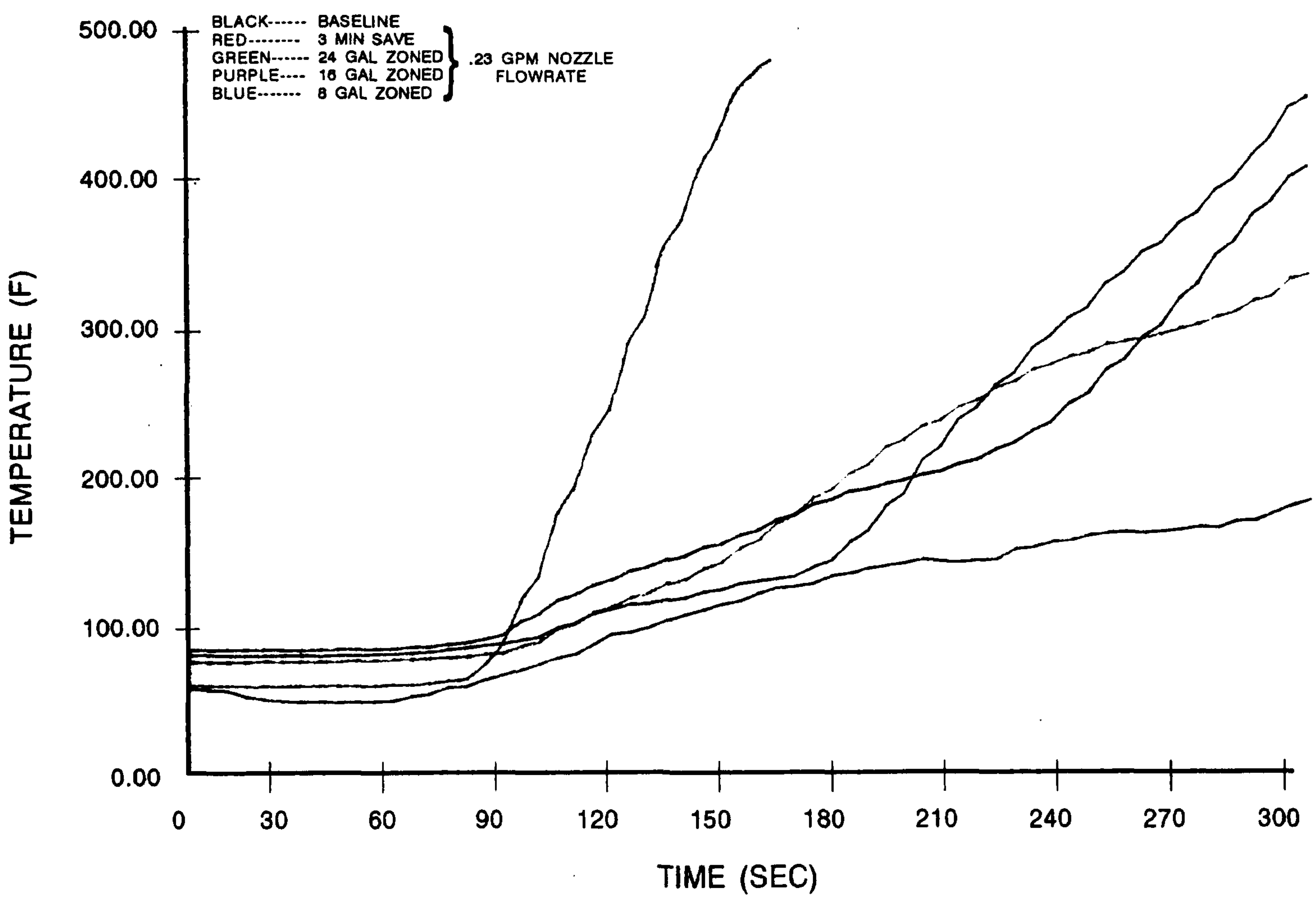


FIGURE 8. TEMP @ STA 400 4'

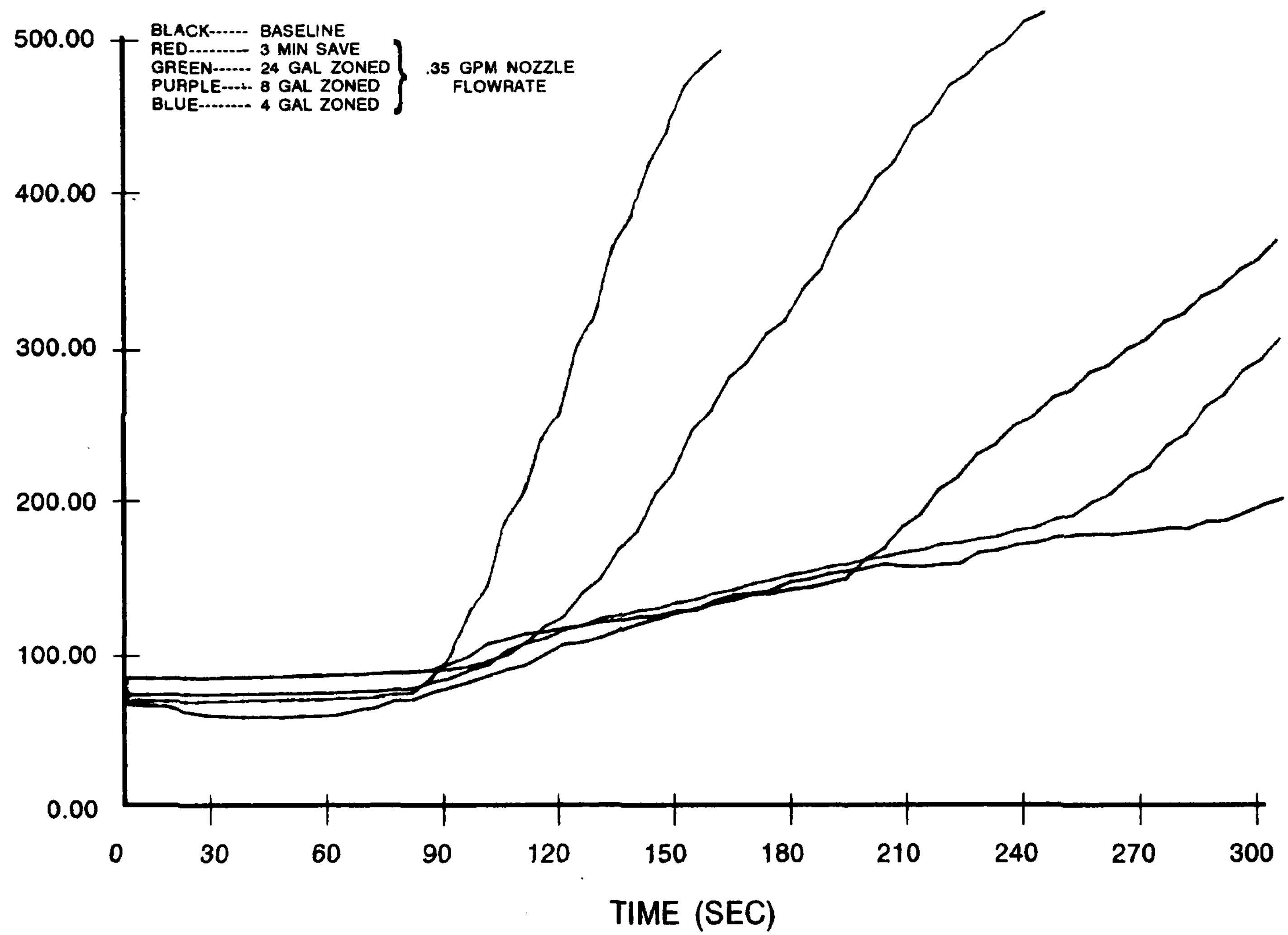


FIGURE 9. TEMP @ STA 400 4'

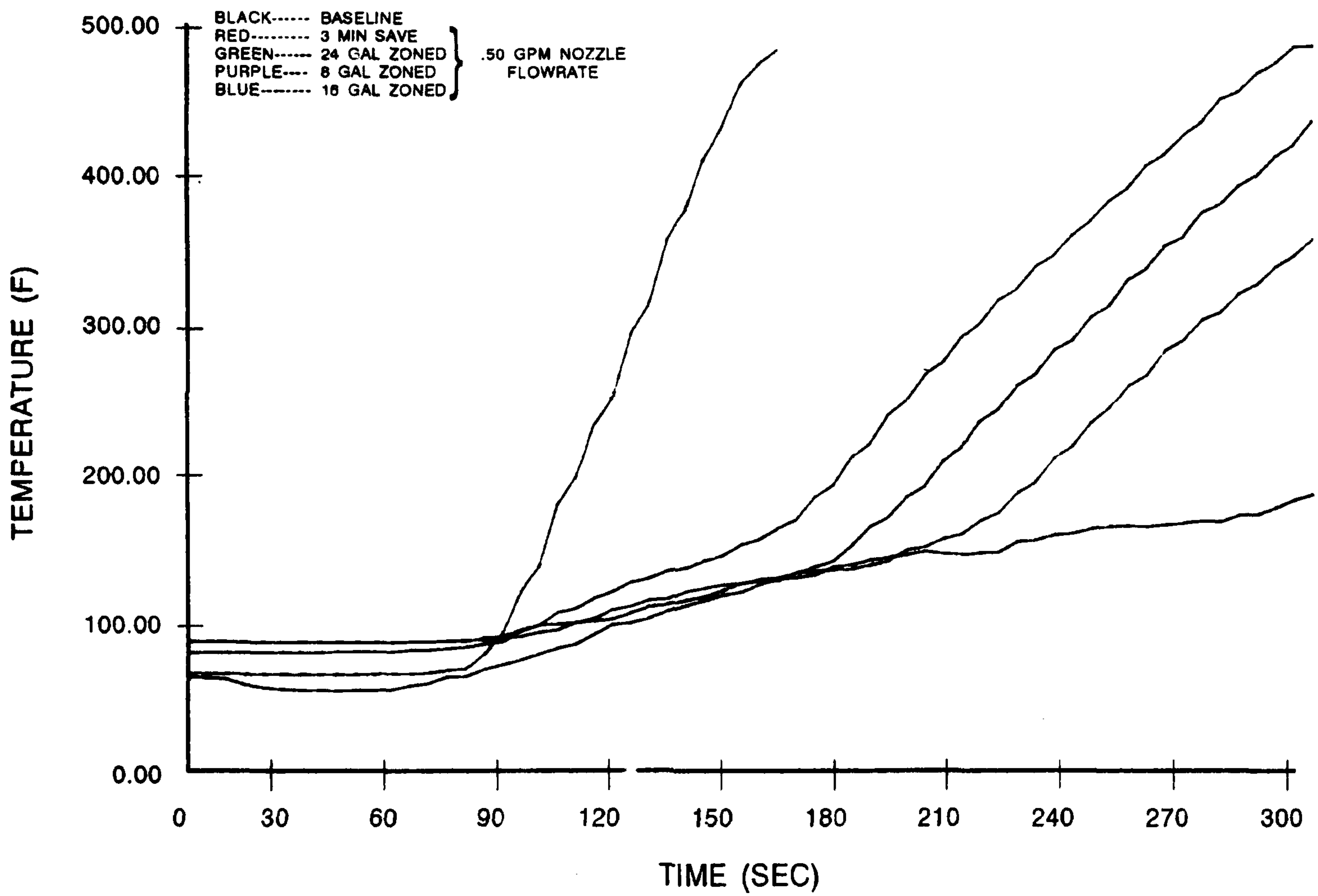


FIGURE 10. CO @ STA 400, 3'6" TO 5'6"

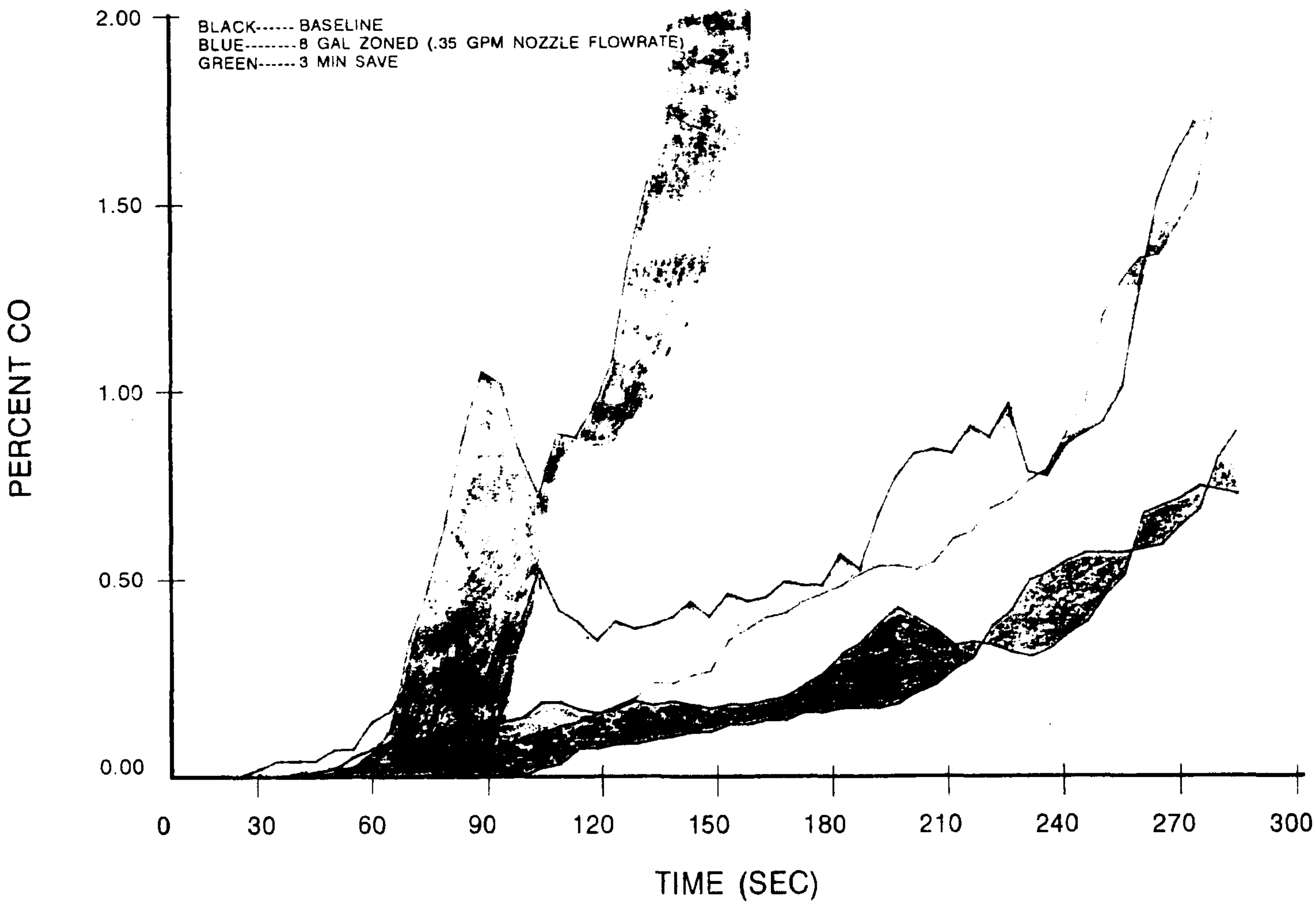


FIGURE 11. CO @ STA 400, 3'6"

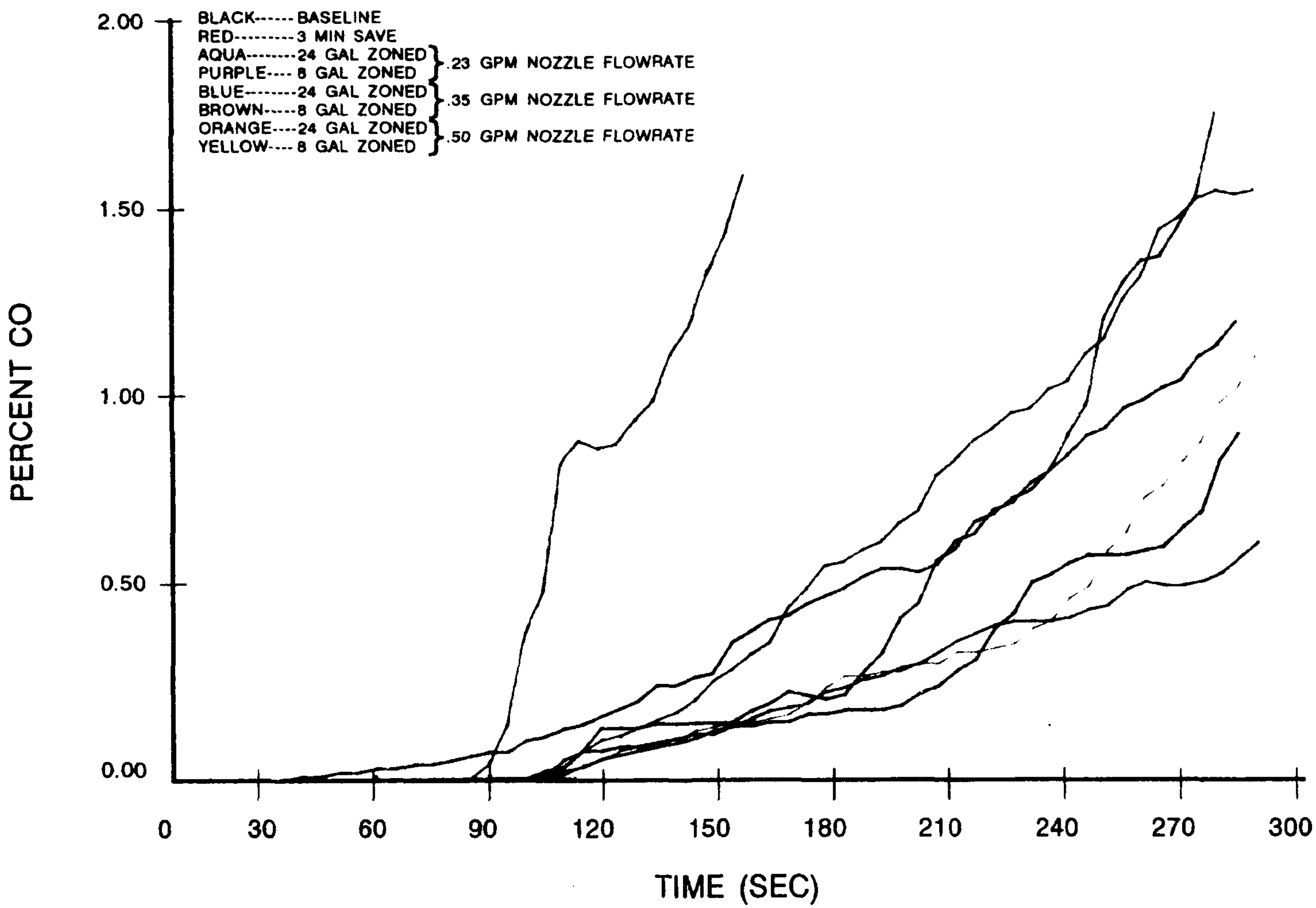


FIGURE 12. CO2 @ STA 400, 3'6" TO 5'6"

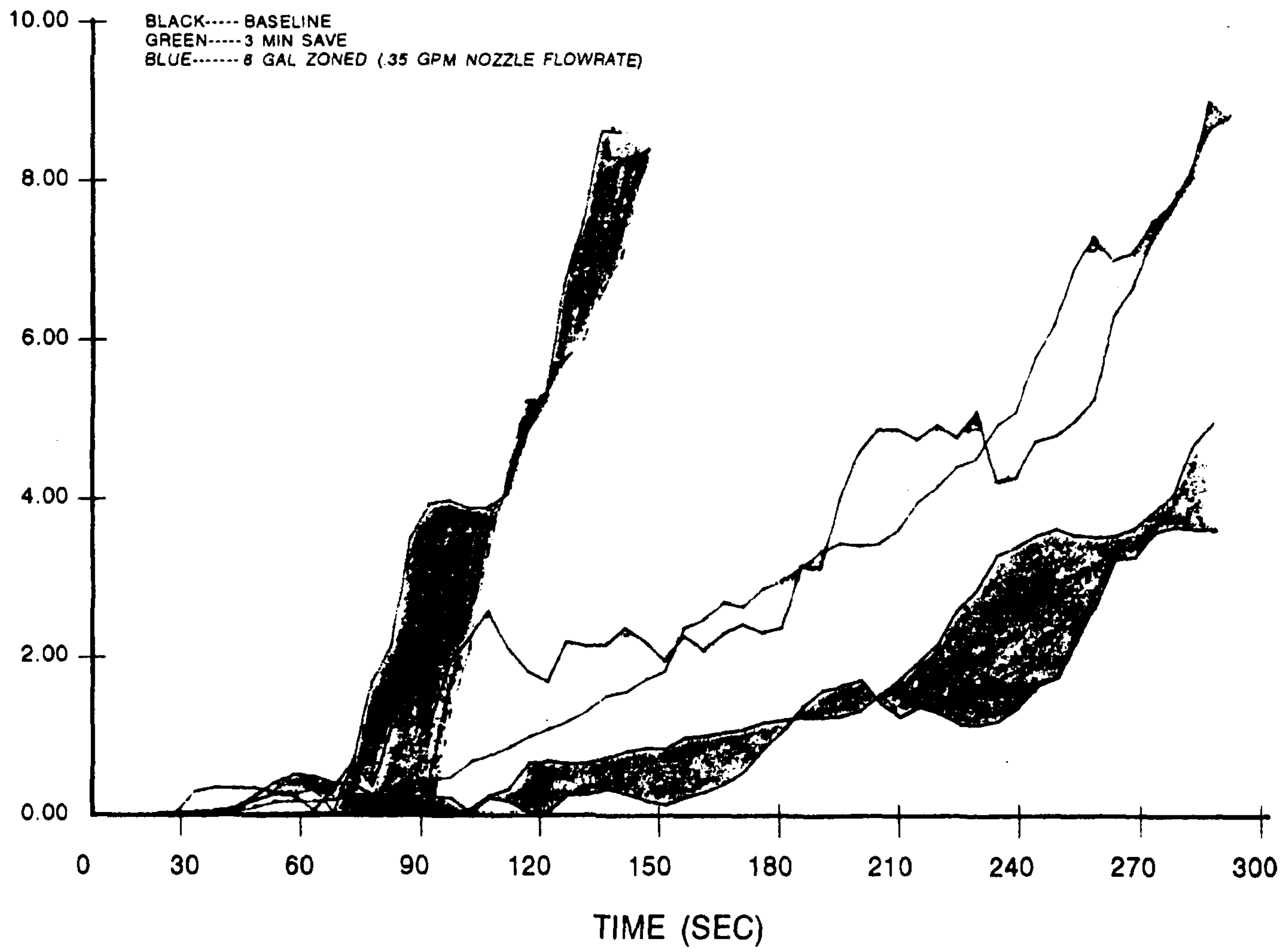


FIGURE 13. CO2 @ STA 400, 3'6"

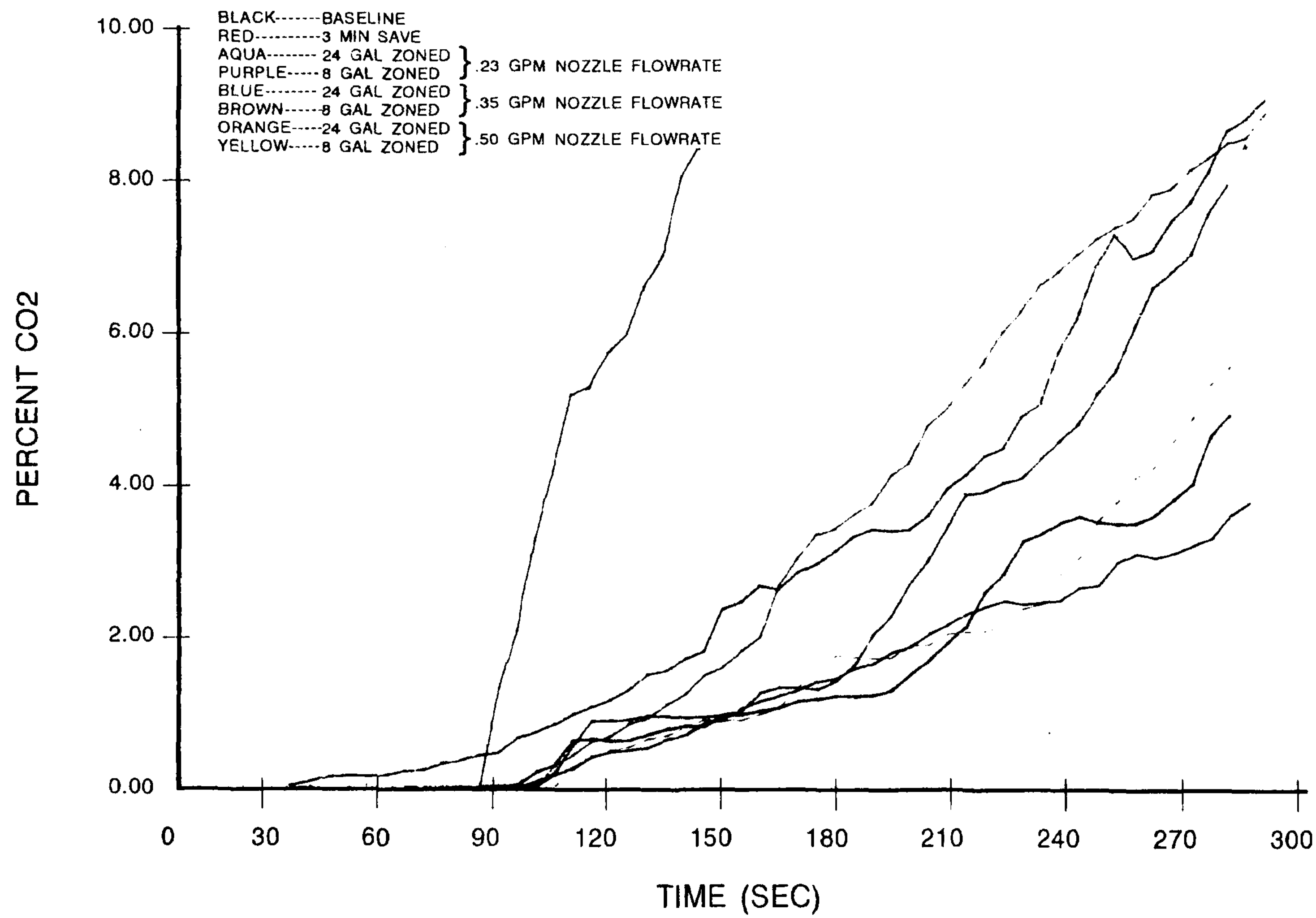


FIGURE 14. O2 @ STA 400, 3'6" TO 5'6"

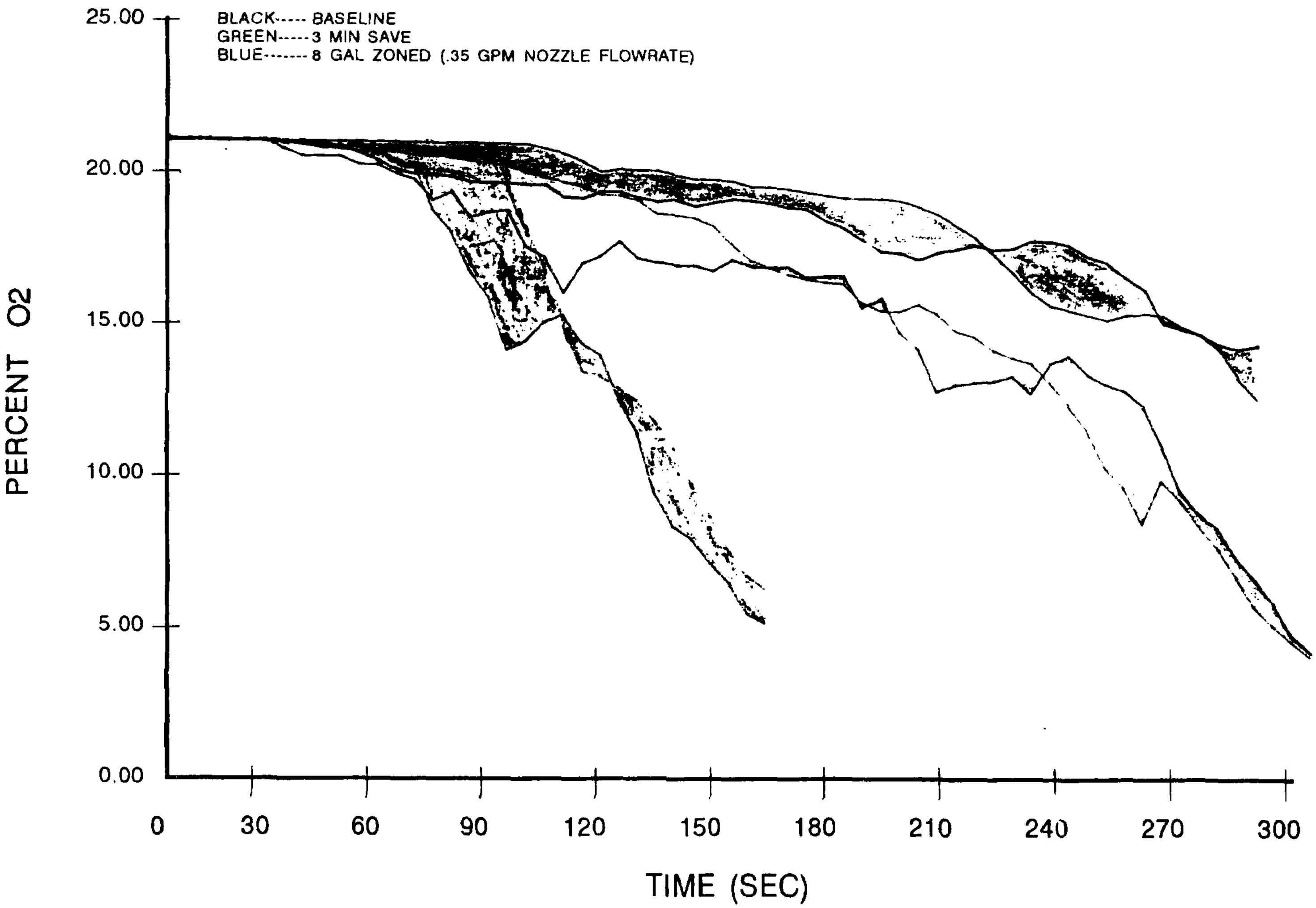


FIGURE 15. O2 @ STA 400, 3'6"

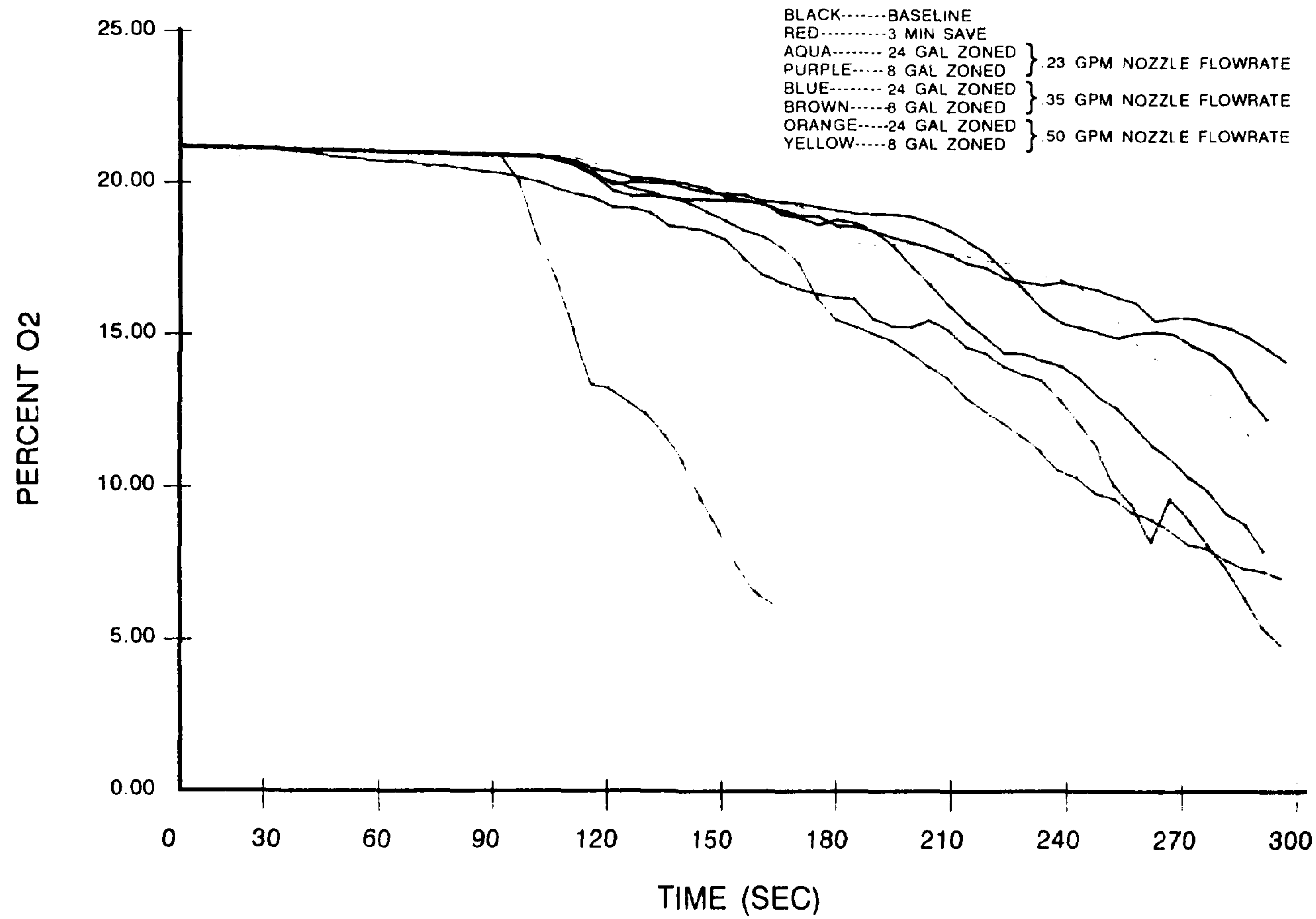


FIGURE 16. SMOKE STA 780 1'6" TO 3'6"

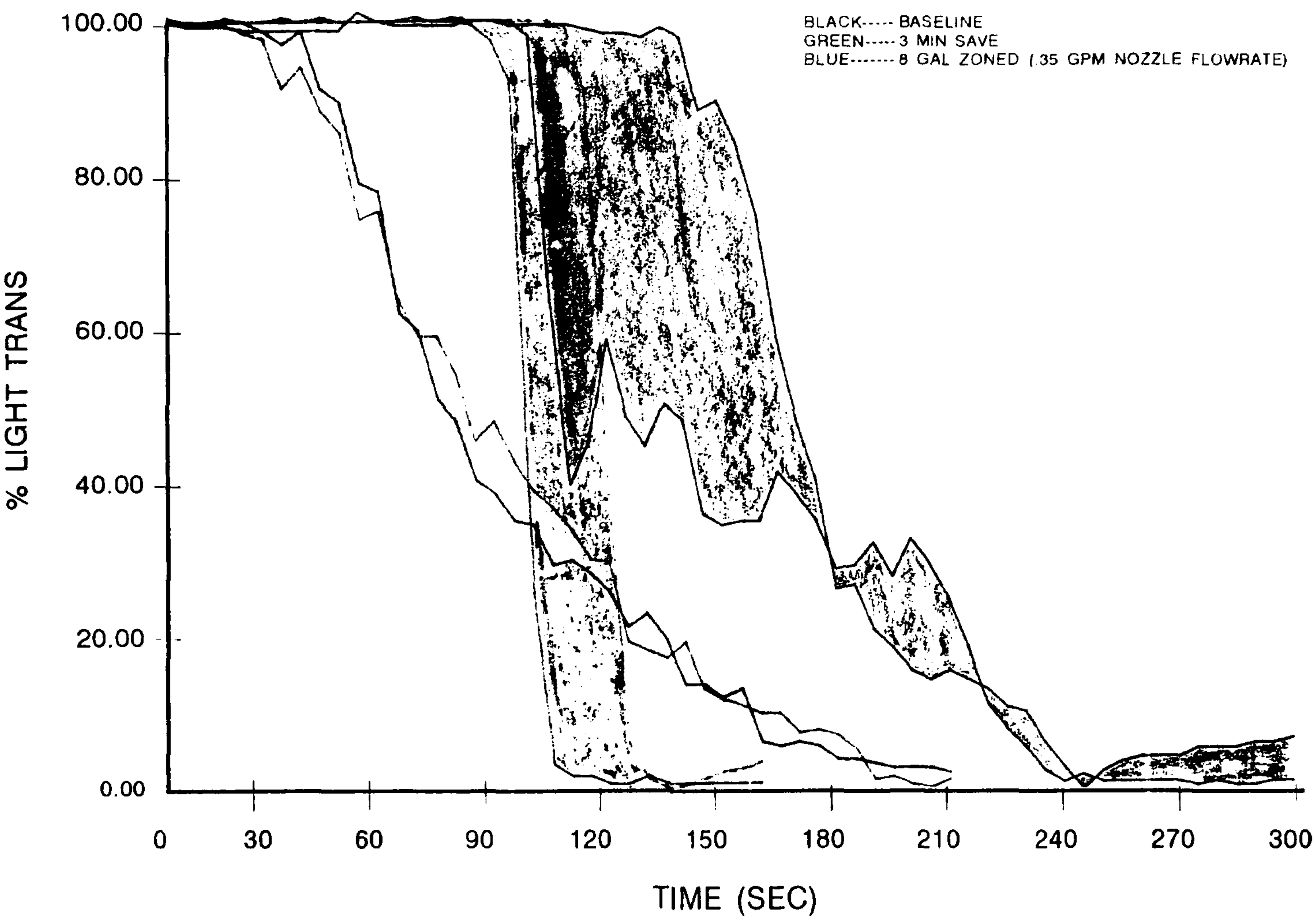


FIGURE 17. SMOKE @ STA 400 3'6" TO 5'6"

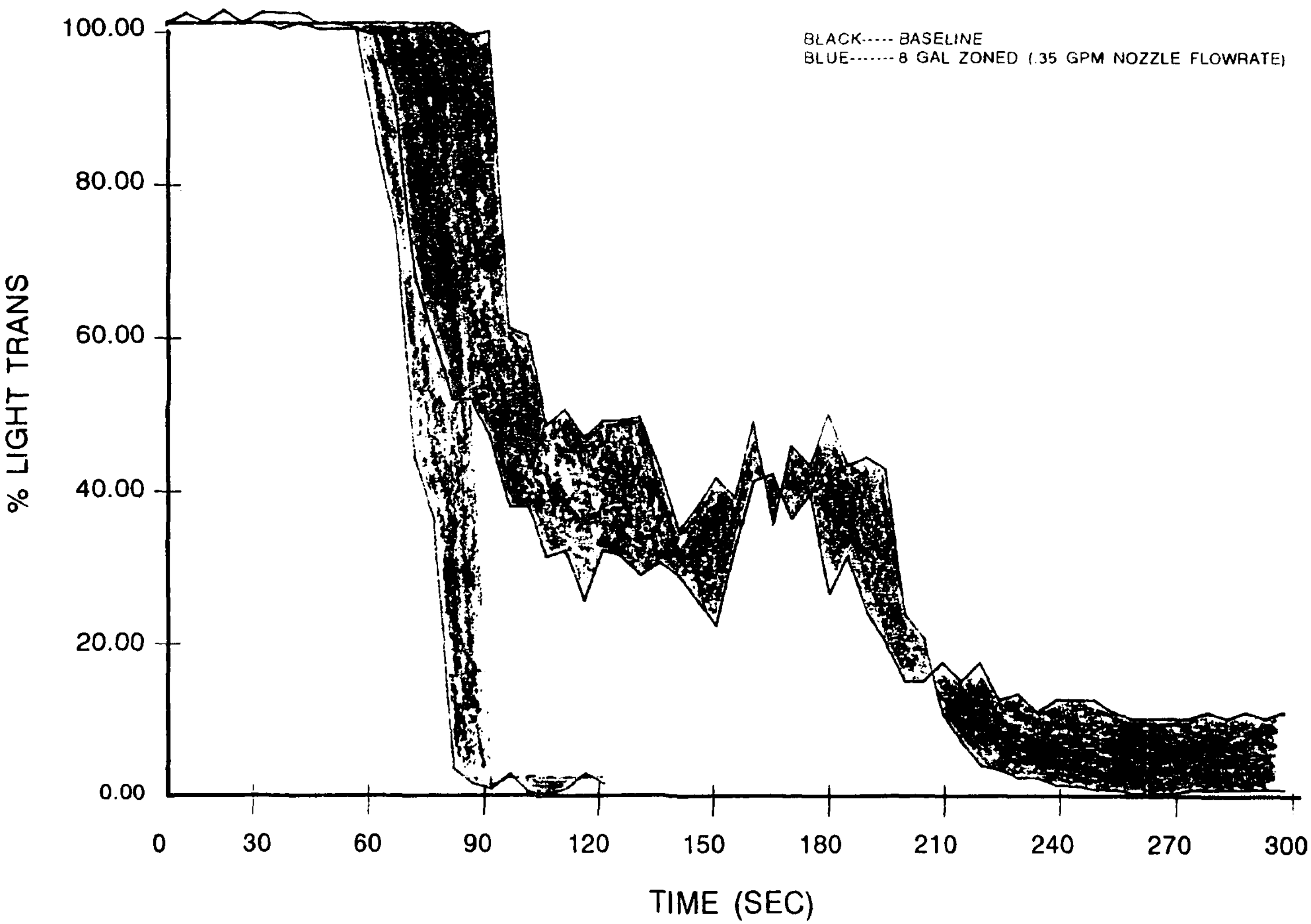


FIGURE 18. SMOKE @ STA 400, 3'6"

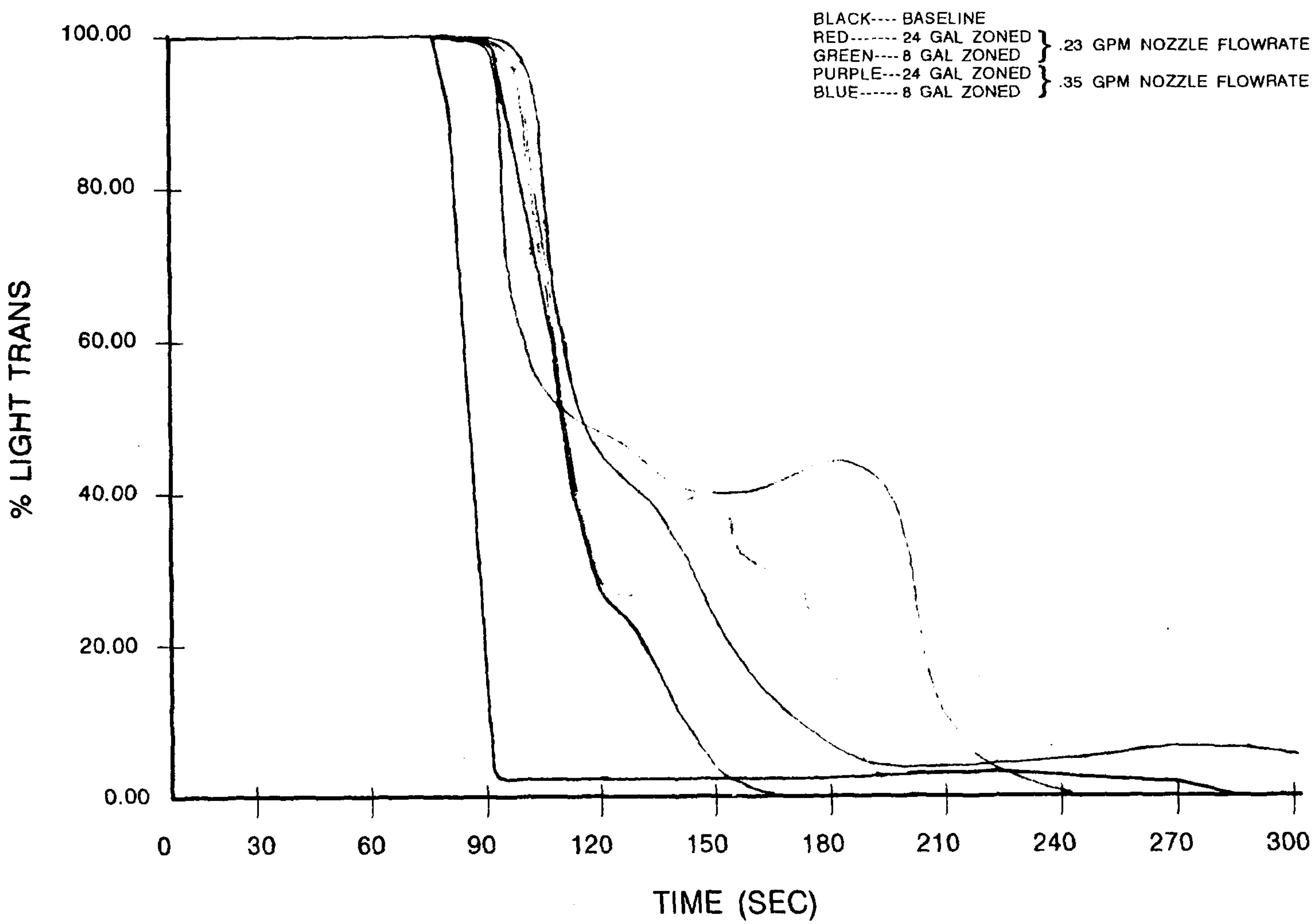


FIGURE 19. FED @ STA 400, 5'6"

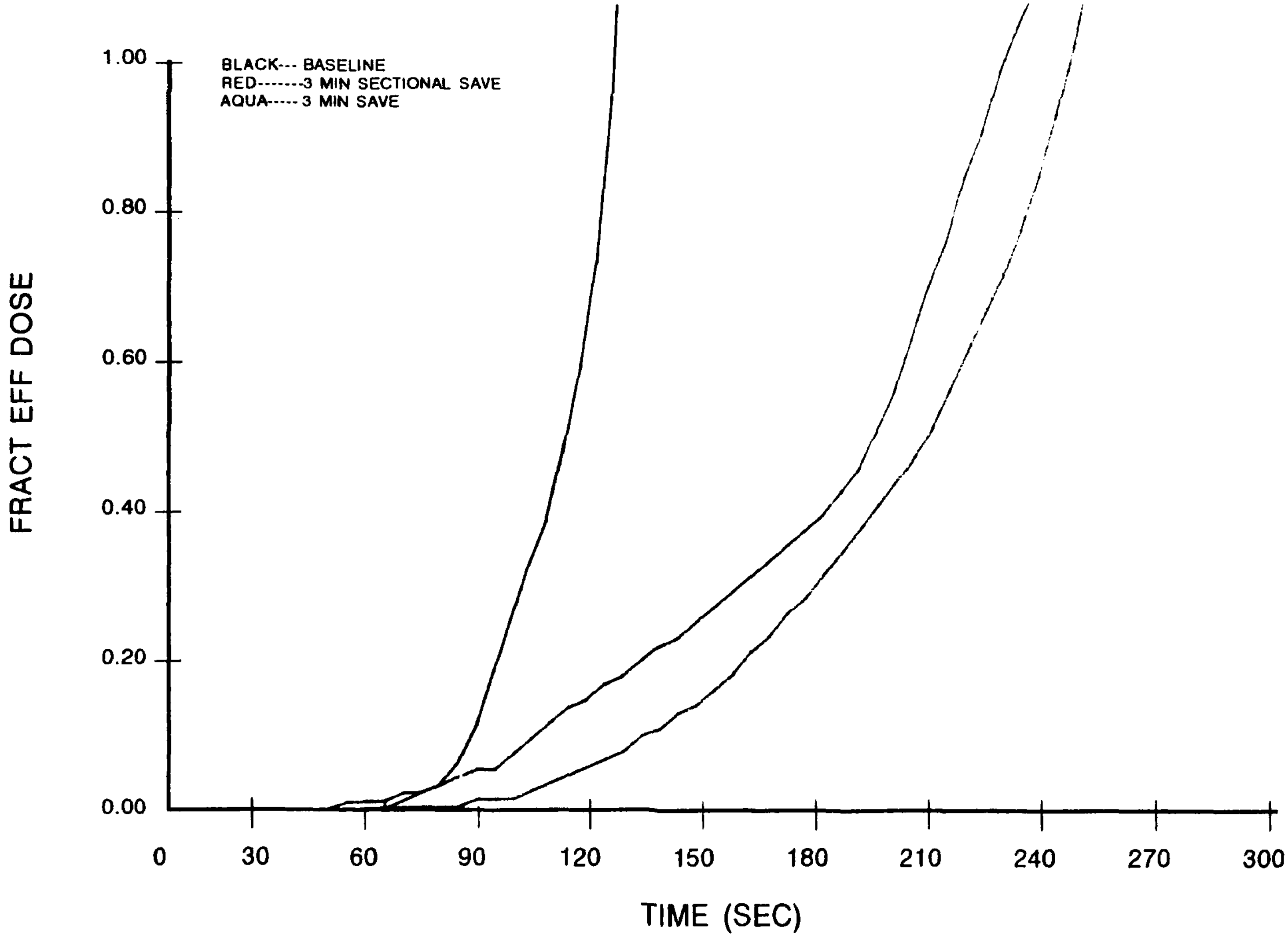


FIGURE 20. FED @ STA 400, 5'6"

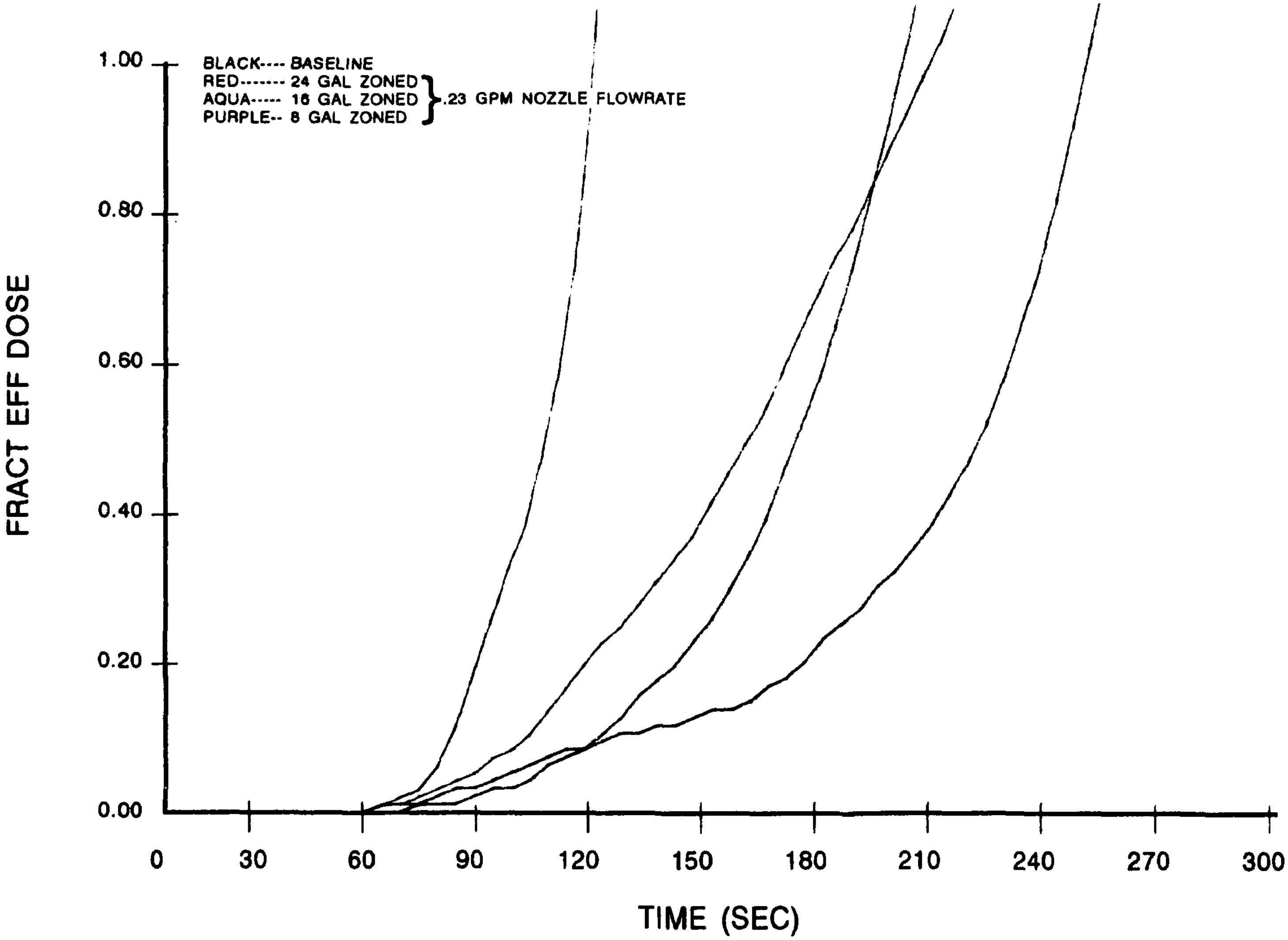


FIGURE 21. FED @ STA 400, 5'6"

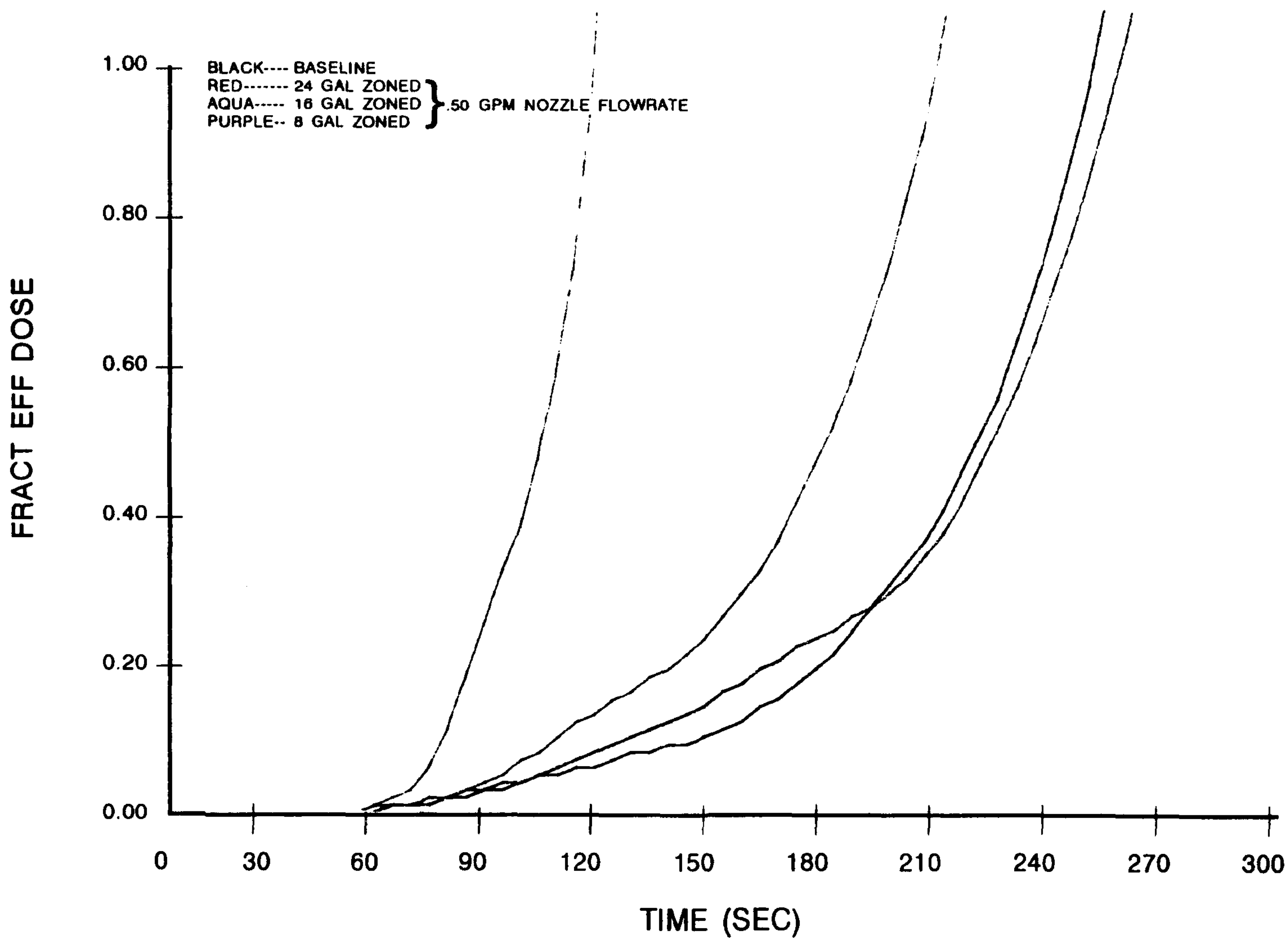
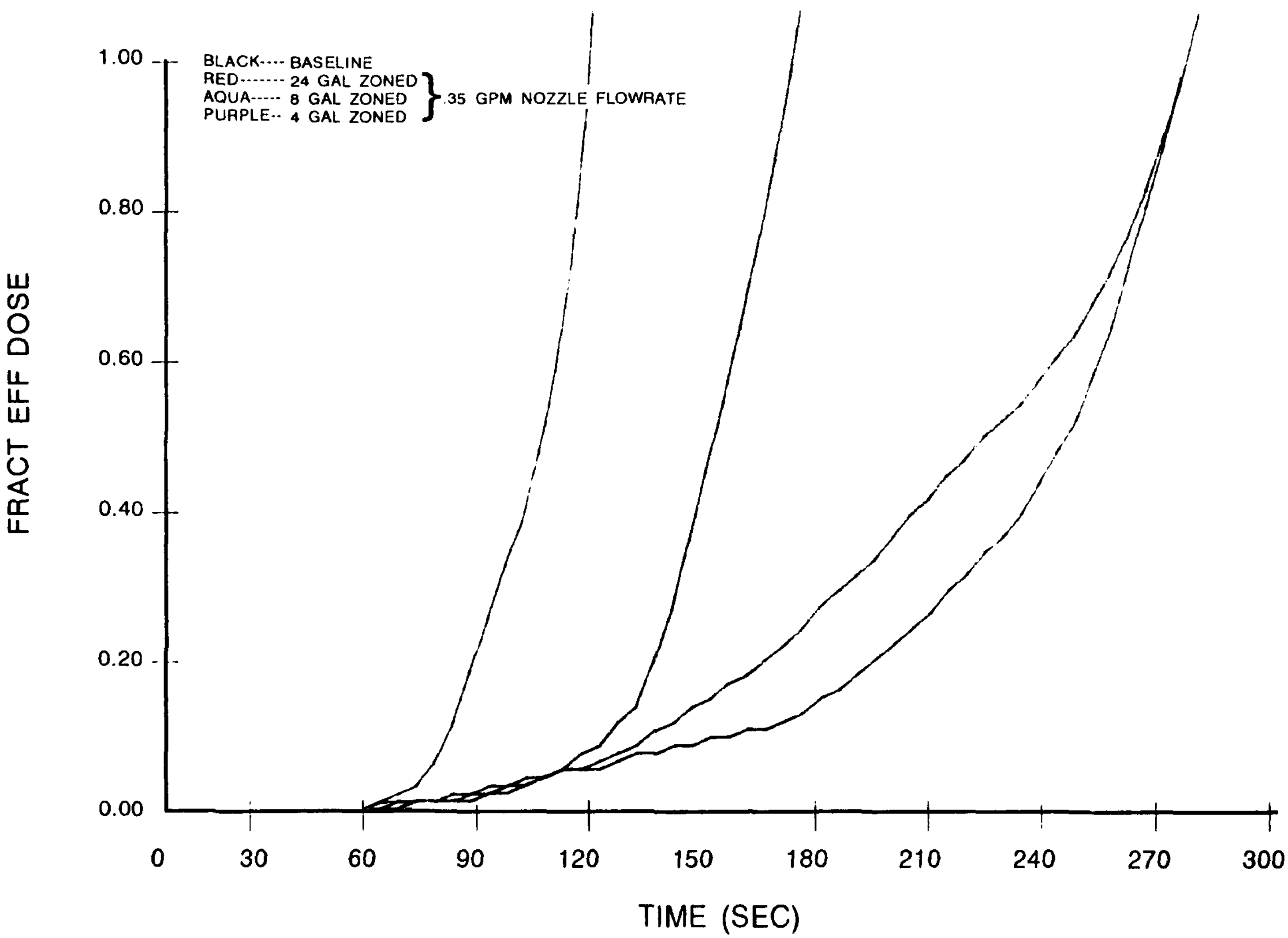


FIGURE 22. FED @ STA 400, 5'6"



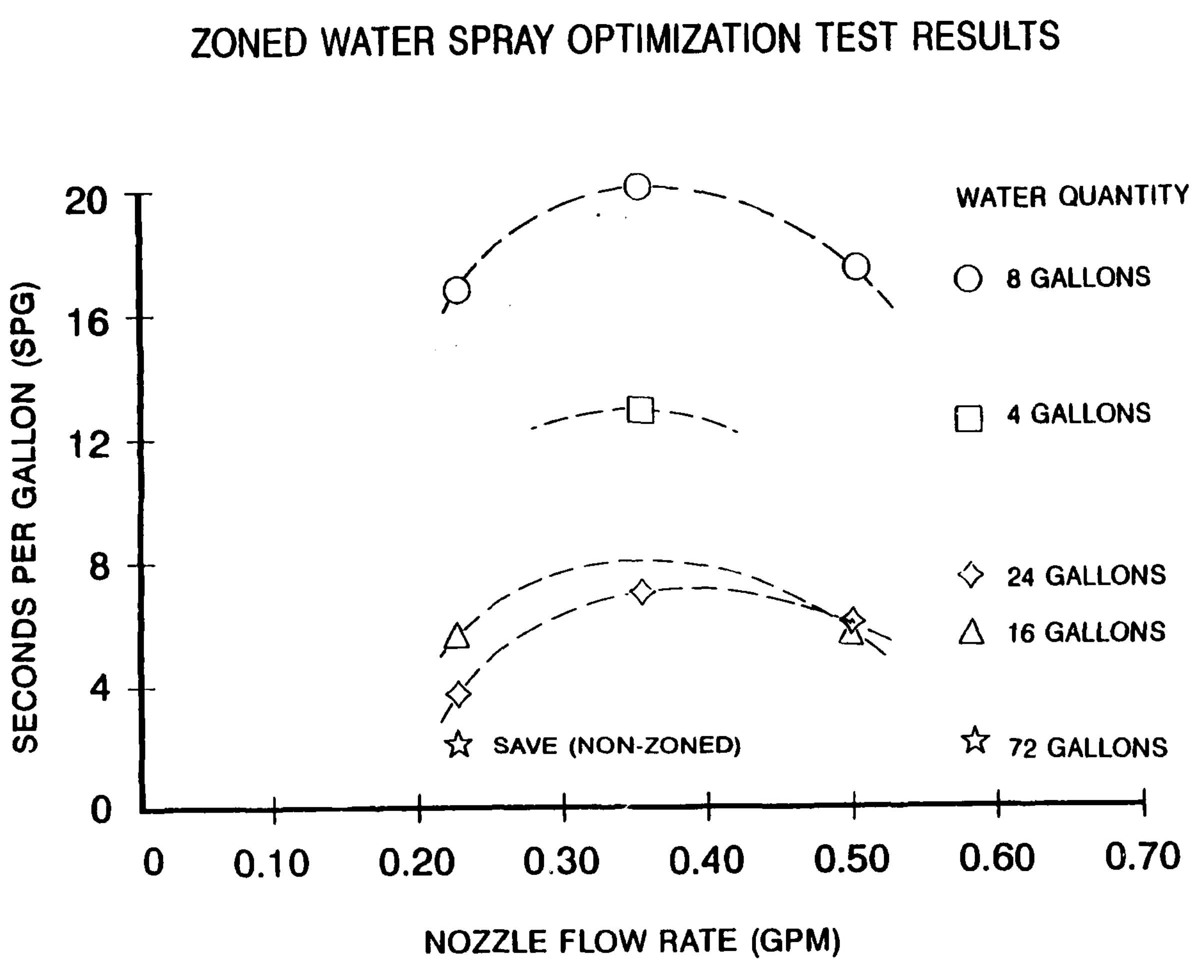


FIGURE 23. SPG VERSUS NOZZLE FLOW RATE